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PROTECTION OF ELECTRICAL AND ELECTRONIC EQUIPMENT AGAINST LIGHTNING INDIRECT EFFECTS ON THE AIRBUS A340 WING

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ABSTRACT

This paper deals with the provisions applied to the Airbus A340 wing wiring against lightning indirect effects. The construction and installation of the wiring's shielding systems are described, and it takes a look at the analysis and tests performed to determine the effectiveness of the measures taken. A first evaluation of the results of the theoretical analysis together with the provisional results of tests indicate a sufficient safety margin between required and achieved protection level.

1. INTRODUCTION

Airbus Industrie's newly developed aircraft A330 and A340 have, as the already flying A320, a complex fly-by-wire system. Failure of, or errors in, such a system may be hazardous. Therefore, the need to ensure that these systems are not affected by a lightning strike is paramount. The increased use of non-metallic materials, like carbon or glass fibre in the construction of the aircraft also means that the inherent screening against the magnetic field of the lightning current is reduced [1].

The protection of electrical and electronic equipment against this effect can be achieved either by filter/protection devices, shielding of the dedicated wiring or both. To apply any method alone would probably be too expensive or just not practicable. Further, any protection method must allow easy maintenance and cater for future modifications without any degradation in the protection performance.

2. LIGHTNING ENVIRONMENT

2.1 EXTERNAL ENVIRONMENT

Lightning strike to an aircraft does in fact happen often enough to consider it as something that with a high probability will occur at some stage in an aircraft's lifetime.

The analysis of, and research into, the nature of lightning is reflected in numerous publications. They give a physical model of the lightning, which is needed for threat assessment and other theoretical evaluations (e.g. [2],[3] and [4]). The model used for the analysis described in this paper is specified in the Advisory Circular 20-136 [4]. It also forms a basis for the certification of the aircraft. Its parameters for a severe single strike are a peak current of 200 kA, an action integral of $2 \cdot 10^6$ A^2s and a rate of rise of $1,4 \cdot 10^{11}$ A/s with a double exponential waveform (component A).

2.2 INTERNAL ENVIRONMENT

Equipment not exposed to a direct lightning attachment will be subjected to the indirect effects of the lightning strike. These indirect effects are described as the "internal environment". The aircraft's internal environment is the result of the lightning current flowing through the aircraft and electromagnetic fields penetrating the skin or existing in open areas and therefore are determined by the external environment. These transient fields induce voltages in the aircraft's wiring. Typical lightning induced voltages and currents on interconnecting wiring are defined in the Advisory Circular AC 20-136 [4]. They are used to specify the equipment transient design level (ETDL), giving the maximum voltage and current amplitudes allowed at the equipment interfaces as well as their waveforms.

Equipment and wiring associated with the A340 wing (Figure 1) have been regarded as being in a severe electromagnetic environment and the equipment has been specified accordingly. Since experience showed that these voltages induced would be harmful, one approach to compatibility is through shielding of the interconnecting wiring.

For the certification of the aircraft, analysis and tests have to show that actual transient levels on the wing wiring are lower than the transient control level (TCL), which is the ETDL minus a safety margin, and therefore the maximum level of lightning induced voltage appearing at equipment interfaces.

3. SHIELDING SYSTEMS

3.1 CONSTRUCTION

Any type of shield for the use in modern aircraft has to fulfill many requirements, a number of which are not related to their shielding effectiveness directly. Their properties are not independent from each other, and an optimum solution for a mechanical requirement could cause a degradation of the shielding performance.

Some restrictions for all kinds of systems in the aerospace industry are due to a lack of space for the installation and the requirement for a minimum of weight. On the other hand, the design shall be mechanically robust and immune to all environmental influences (hydraulic fluids, salt water, etc.). It must also be taken into account that the shield cannot be installed in a straight run, but usually has to go around equipment or pipes (Figure 2). The wires must be kept in place in the harness under all conditions without the danger of chaffing. Additionally, the need for maintenance work should be kept to a minimum and it should allow for modifications to, or addition of, cables.

3.2 THE A340 WING

The above mentioned and to some degree conflicting requirements, led to a solution for the A340 wing, where two different shields have been used.

The main cable looms from the fuselage on the front and rear spar to the wingtip are mainly routed in open ducts with four separate channels, known within Airbus Industrie as "raceways" (Figure 3). These are made of an aluminium alloy and have a protective coating. They come in three different sizes to cater for the growing size of the looms closer to the wing root. The channels are filled up to approx. 65% of their height. Over the wing span, the raceways are mounted on brackets as segments of a length between 150 and 700 mm, depending on the constructional needs. Two neighboring raceways share one bracket. The gaps between two segments are usually 4 mm or less.

The second type of shield used is that of a braided conduit made of nickel plated copper. They are used for the short breakouts where wires run from a raceway to a piece of equipment or where the routing around corners or many bends over a short distance prohibit the use of raceways. This harness system can be equipped with a range of special conducting adaptors and connectors. These allow an electrically low resistance connection to equally furnished equipment housings and to the aircraft structure, thus providing 360° circumference bonding.

When cables are led from raceways into a conduit, the end fittings of the conduits are mounted on brackets as close as possible to the raceway, so that the cables run only over a very short distance outside of a shield.

4. ANALYSIS OF THE SHIELDING EFFECTIVENESS

4.1 UNPROTECTED WIRING

As already mentioned, the use of wiring routed outside of the shielding systems in the wing has been avoided as far as possible. In that sense, the wires are only routed unshielded in the gaps between raceways or conduits and raceways. Over the wing span the accumulated length of gaps has been limited to some 140cm in the leading edge and 70cm in the trailing edge. The greater length allowed in the leading edge is the result of the better inherent shielding by the metal skin, whereas the trailing edge is a more or less open area, which provides little or no attenuation of the lightning current's electromagnetic field.

4.2 BRAIDED CONDUITS

The decisive parameter for the shielding effectiveness of the braided conduits is the transfer impedance (Z_t). In the frequency domain, Z_t is dominated by the resistance in the range below 1 MHz and by the transfer inductance above those frequencies [2]. Figure 4 shows the transfer impedance as a function of the frequency.

The DC-resistance depends on the volume of metal of the shield. A low resistance calls for a dense, but heavy and less flexible shield. Other decisive factors are the optical coverage and the weave angle of the braid. A high optical coverage and a small weave angle improve the shielding effectiveness, but also decrease the flexibility.

The braided conduits in the A340 wing have an optical coverage of about 90% and a DC-resistance of less than 10mΩ/meter. The transfer impedance, as given in the manufacturers data sheet, is 5 to 10mΩ/meter up to a few MHz with a significant increase in Z_t beyond 10MHz. The low transfer impedance at the bottom of the frequency range is more important. Though the lightning energy is spread over a broad spectrum, the peak energies in the case of induced voltages are in the 50kHz to 100kHz band [1].

The overall performance of a shield also depends on the low resistance connection of the conduits to the back shells of adaptors and connectors, of the sockets to the equipment and the shielding effectiveness of those elements themselves. A table with the transfer impedance of typical aerospace cable connectors is given in [2].

4.3 RACEWAYS

4.3.1 Theoretical Analysis

The purpose of the calculations is, to assess the into the wiring induced transient voltages appearing at equipment interfaces. They are compared with the protection measures to give a first indication of the possibility of over- or undersized protection.

The calculations are based on the distribution of the lightning current in the wing. With certain assumptions it is possible to represent the three-dimensional wing structure as an array of parallel wires [2]. Since there are different materials, resistance values and a corresponding diameter have been assigned to each wire. Those cuts through the wing were made at four points (ribs), each representing a section of the wing (Figure 1).

With the self-inductance of each conductor and the mutual inductance between any two, a system of differential equations can be set up by Kirchhoff's law. These differential equations were solved by a computer code especially developed for lightning assessment purposes by Deutsche Airbus in Hamburg. The code gives the current and its time derivative versus time in each conductor. It then calculates the time derivative of the magnetic flux in a specified wire loop, giving the induced voltage. The way in which the current changes within a given time depends on the change of the lightning current during that time, as well as the geometry and material of the wing in the chosen cross-section. For the wing assessment, a model consisting of up to 585 parallel wires, leading to 584 coupled differential equations was used.

To calculate the voltage induced into cables, a diagnostic wire grounded at one end is assumed to run parallel to the structure within the cross-section of the wing at the position of the shielding system . The calculations were done considering that the wires run in- and outside of a shielding system.

The magnetically coupled voltage into this wire is the result of the time-dependant rate of change of the magnetic flux through the plane between a wire representing the structure and the diagnostic wire. The total induced voltage also contains a fraction generated by the voltage drop U_r along the structure. The worst case calculation for this is to multiply the lightning current $I_L(t)$ by the resistance R_L of the wire representing the wing. This voltage is added to the magnetically induced voltage. The reduction of the resistive fraction by the skin-effect for highly conductive materials has not been considered here. Since U_r is negligible compared to the inductive coupled voltage, a change in that fraction is negligible, too.

4.3.2 Results of Analysis

For the purpose of the comparison between the results of the analysis and the equipment protection level, braided conduits, where they have been installed, have been assumed to have the same shielding effectiveness as the raceway system. For the wing structure, the computations were done for several configurations (e.g. flaps/slats extended or retracted). Examples of these are shown in Figure 5.

The results of the calculations are the induced common-mode voltage in a diagnostic wire and the current flowing through the raceways. Table I shoves these values for the examples above at the four cross-sections of the wing. For 1m of exposed wiring, the calculated voltages for wires outside of a shielding system usually range from approx. 130V in the leading edge up to 480V in the trailing edge. This confirms the need to put a more stringent limit on the accumulated length of gaps between raceways in the trailing edge.(see chapter 4.1) For cables routed in raceways, these induced voltages are reduced to less than 10V per meter of wire for all areas. Therefore, it can be said that the transient amplitude on a wire is mainly determined by the length over which it is running outside of a conduit or raceway.

The results of the computations were used to draw up a list of the transient voltages appearing on each wire of the electrical systems related to the wing, according to the theoretical analysis. For this list, the length of each wire in different areas of the wing was determined and the voltages induced in each area were added up, as shown in Table II.

4.3.3 Tests

For the raceway system, not enough data about the shielding performance (i.e. the transfer impedance) were available. Therefore, tests were carried out at the University of Hannover, Germany, where the transfer impedance was to be determined from measuring voltages induced into the wires when a current of a known value flows through a raceway segment.

The induced voltages were picked off wires put into each type of raceway. Two wires were fixed in each of two chosen channels at 65% and 80% of the height of the respective channel. Pulse currents of ca. 25kA with a damped sine waveform with frequencies of ca. 16kHz and 114kHz were injected into the segments. The tests were carried out on a single raceway with a length of about 1m and on two raceways with a combined length of about 1m, separated by a gap typical for the actual installation in the wing. The segments were mounted on brackets with fasteners in accordance with the original assembly.

Though the measurements have not been completely assessed, the first results indicate an excellent shielding effectiveness of the design. For each type of raceway and for wires running at up to 65% of the channel's height, the values for the transfer impedance are much less than 10mΩ/m in the tested frequency range. The coupling proved to be mainly inductive, as di/dt*L is the main portion of the induced voltage (0,07mΩ/m plus 0,71nH/m inductance).

Comparing the results of the calculation and the tests on a raceway gives an estimate of the value of the computer model. The induced voltages, in relation to the current flowing through the raceway, in either case give a difference between calculation and tests of approx. 10%. The voltages therefore expected at the equipment interfaces are usually ca. 320V or less.

5. PRODUCTION AND QUALITY CONTROL

5.1 INSTALLATION

While the shielding effectiveness of the shield itself is the result of its design, the performance of the in the aircraft fitted system depends very much on the design of the installation and its low bonding resistance. It must ensure that the shields can be fitted well during production process and that the assembly does not degrade beyond a limit during its life-span.

5.2 QUALITY CONTROL

To function as a shield against lightning current magnetic fields, raceway segments and braided conduits have to be bonded well on both ends to the aircraft structure [5][6]. The problem is to guarantee this low resistance passage after the systems have been built in.

Electrically, the installed shield bonding resistances act as a parallel connection in a conventional bonding measurement (Figure 6). Therefore, a low reading on an ohm meter would not give the true values.

The solution is to induce a current of up to 100A into the loop formed by the shield and the aircraft structure, where the joints form a serial connection (Figure 7). A measurement of the voltage drop across one joint would,together with the current, allow to calculate its bonding resistance. In reality, the whole procedure is more complicated, because it was required that the measurement device should not touch the surfaces of the raceway or brackets.

At the Deutsche Airbus factory in Bremen, a tool is now used that has been developed by a company in Germany, on the initiative of the Deutsche Airbus lightning protection specialists. It allows to measure the bonding resistance of the complete loop, where each joint has a specified maximum value of 2mΩ. The resistances of the metallic aircraft structure and shield in this loop have been regarded as insignificant for this measurement. Though it has been especially designed to measure the bonding resistance of raceways, it also can be used for braided conduits connected to brackets or equipment.

6. DISCUSSION

The installation and theoretical evaluation of the protection measures applied to the A340 wing wiring have been described. This is not a complete review of the protection scheme of the aircraft and its systems, but concentrates on how the induction of damaging transients into the wiring has been countered. The assessments use some simplifications. The interaction between lightning current and aircraft structure has been reduced from a three- to a two-dimensional model. All wires are assumed to be routed at the maximum allowed height in a channel. Possible shielding effects by hydraulic pipes and other metal framework have not been considered.

The induced voltages obtained from analysis and tests are common-mode voltages. When compiling the list of induced voltages for each wire at the equipment interface, the wires have always been considered to be single and without an individual shield. The voltages induced between the wires of a twisted two or multiple wire circuit (differential-mode) are assumed to be lower by a factor of 10 or more.

Together with the first test results, it can be said that the protection looks adequate. A final judgement about the value of the theoretical work can only be given after full aircraft tests have been performed and evaluated at a later stage in the program.

7. ACKNOWLEDGEMENTS

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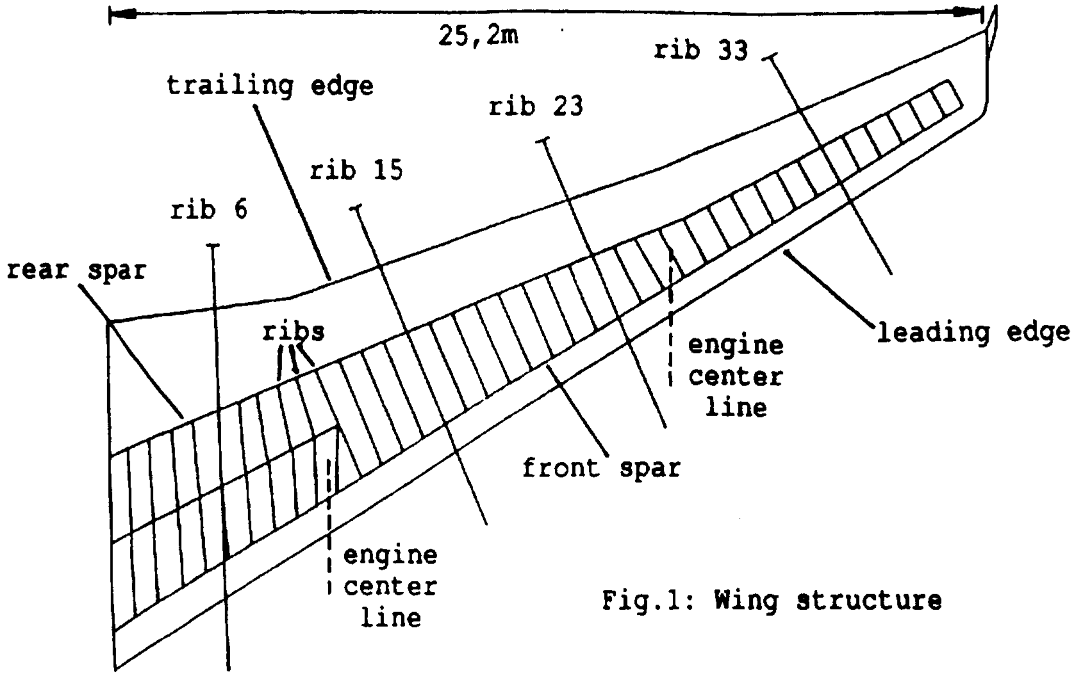


Fig.1: Wing structure

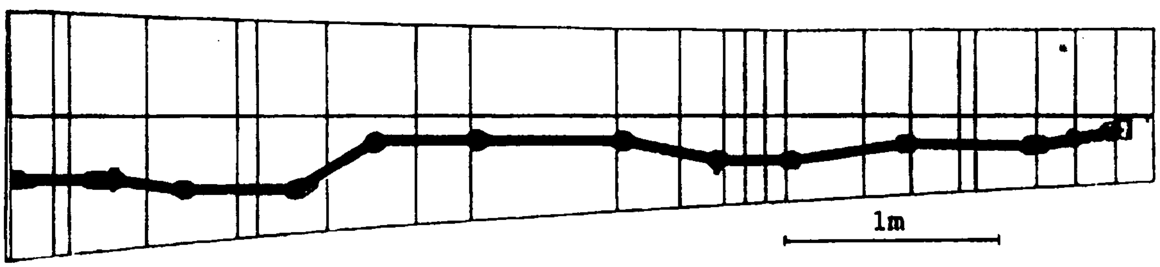
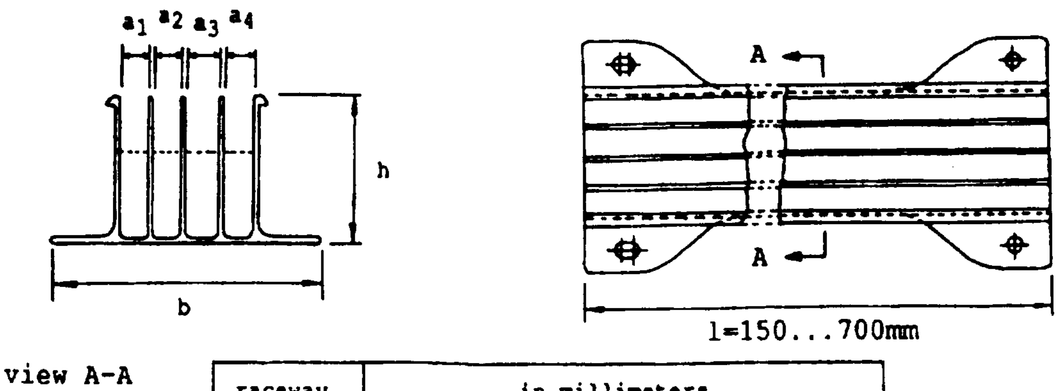


Fig.2: Installation of raceways on the A340 wing, front spar



raceway type	in millimeters					
	b	h	a_1	a_2	a_3	a_4
II	89	33	9,25	8,5	20,75	9,25
V	76	23	8,5	8,5	9,25	8,5
VII	79	43	8,5	8,5	9,25	8,5

Fig.3: raceway segment

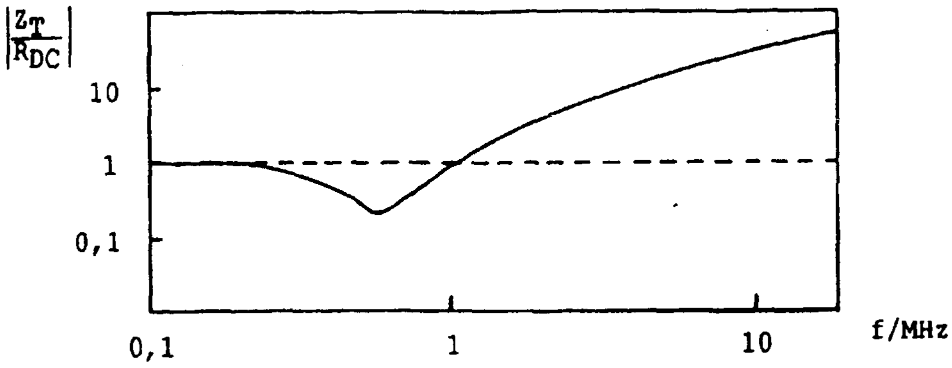


Fig.4: Braided conduit transfer impedance Z_T as a function of the frequency

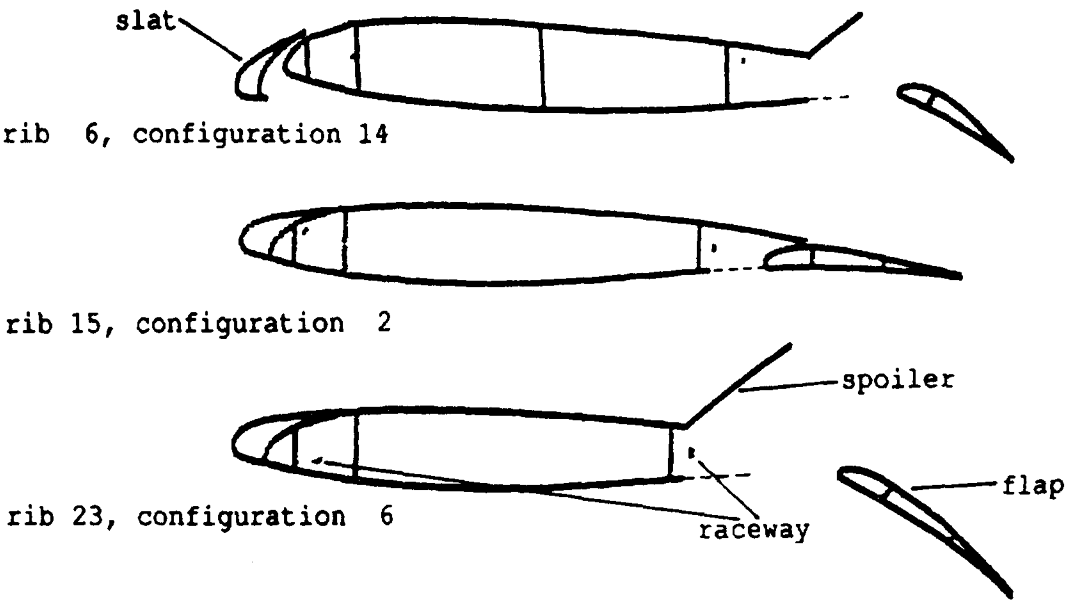


Fig.5: Parallel wire model of different wing configurations

Table I: Induced voltages and raceway currents

Config.	Induced Voltage (V/m)								Current through raceway (kA)							
	rib 6		rib 15		rib 23		rib 33		rib 6		rib 15		rib 23		rib 33	
	L/E	T/E	L/E	T/E	L/E	T/E	L/E	T/E	L/E	T/E	L/E	T/E	L/E	T/E	L/E	T/E
14	<.1	.4	.49	6.8	<.1	9.3	.11	1.7	.11	-.07	.52	2.6	.42	3.5	.63	4.7
2	<.1	.42	0.1	3.6	0.1	5.3	0.2	1.8	.06	-.09	.07	2.2	0.6	3.1	0.8	5.2
6	<.1	.31	0.1	7.1	0.1	9.8	0.2	1.8	.06	-.07	.06	2.7	0.6	3.7	0.8	5.2
5	2.7	19	3.4	353	31	487	43	231	configuration as 6, but no raceway							

L/E - leading edge
T/E - trailing edge

Table II: Calculation of induced voltage at equipment interface

Subject/Component	signal	wire type	length [m]	area	voltage induced (calc.)	remarks
RH flap wing tip brake wire no. 1 1-wire cable	DC	CF18	0.32	32	4.5	in conduit
			0.98	32	13.8	in raceway
			8.65	28	89.1	"
			2.77	24	1.3	"
			2.07	24	0.9	in conduit
			0.33	22	0.1	junction box
			0.56	24	0.3	in conduit
			0.2	22	0.1	box
					110.1 V	total voltage

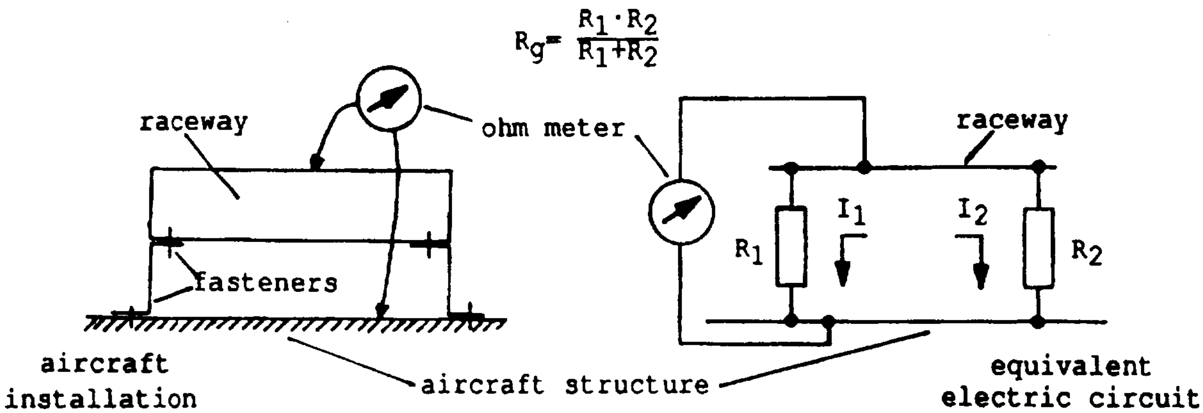


Fig.6: Bonding measurement with ohm meter

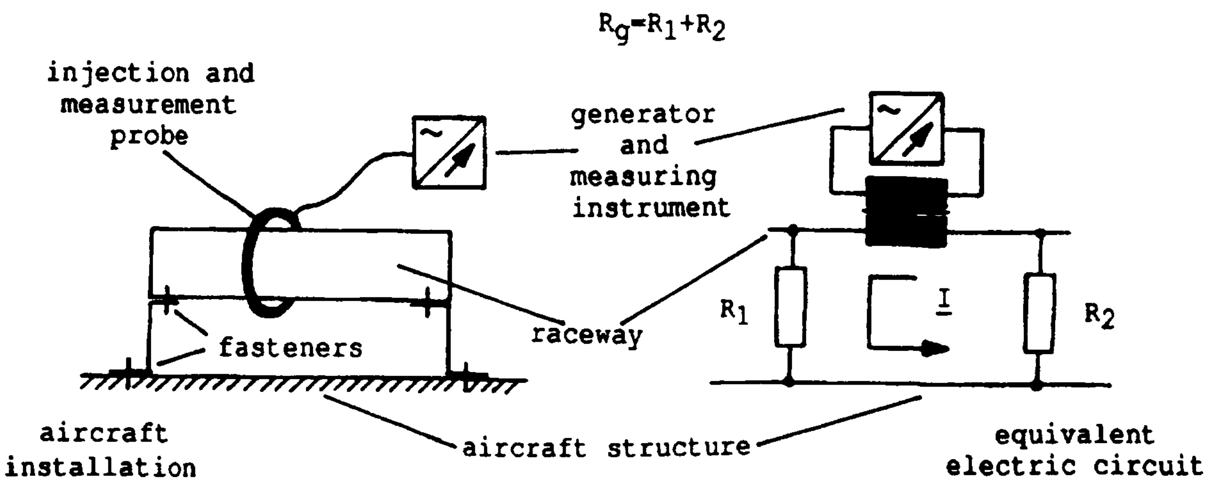


Fig.7: Bonding measurement with special tool